HL Analogue and digital techniques

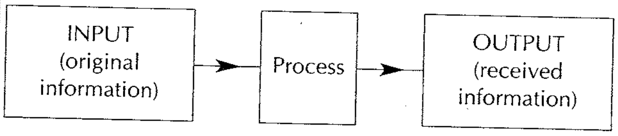
ANALOGUE AND DIGITAL

Information comes in many forms, for example:

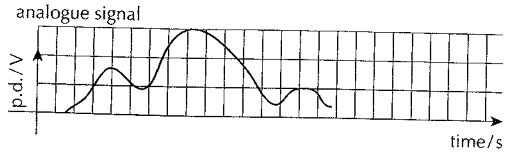
- text
- pictures
- speech/sound/music
- video
- a mixture of all of the above.

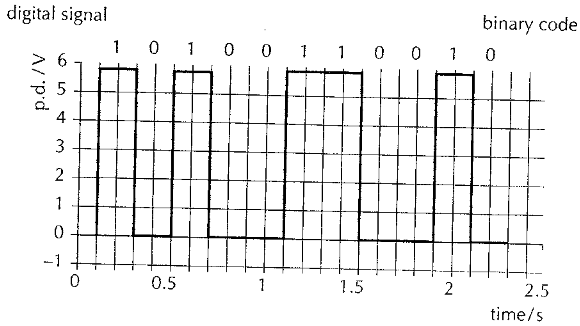
The transfer of information between two people requires the use of agreed codes. In a language, the sounds of different words are an agreed code for different concepts. Different alphabets are agreed codes for the sound of different words in written form.

The use of technology for the storage, processing and transfer of information involves converting the original information into a different form (often an electric or electronic **signal**), which can be converted back as required.



This can be achieved using **analogue** or **digital** techniques. Analogue techniques involve codes and signals that can take a large number of different values between given limits. The analogue signal continuously varies with time.





Digital techniques involve codes and signals involve a large number of **binary digits**, or bits. Each bit can only take one of two possible values. (1 or 0; High or Low; ON or OFF; True or False). Eight separate bits of information are called a **byte**. Larger quantities of information are measured in kilobytes, megabytes, gigabytes etc. A digital signal repeatedly changes between the two available levels.

Method of storage	Typical source information	Overview of process	Comments	Analogue or digital
Photocopying	Text or pictures	Optical and electrostatic processes are used to create a hard copy of the original document.	The process is not 100% accurate. A photocopy of a photocopy will be further reduced in quality.	Analogue
Microfiche	Text or pictures	Optical process used to photograph a large number of original documents to be held miniaturized form.	An optical microfiche reader is used to access the information.	Analogue
LPs ('vinyl')	Music or speech	Sound variations are stored as variations in a track on the LP.	Dust and/or scratches alter the output quality.	Analogue
Cassette tapes	Music or speech	Sound variations are stored as variations in the magnetic field orientations in the tape.	Each time the tape is played, the quality is slightly reduced. The tape can be stretched or damaged.	Analogue
Floppy discs	Text	Different characters are stored as series of magnetic variations in the disc. Only two possible variations are utilized.	Magnetic fields can corrupt the data stored on a floppy disc.	Digital
Computer memory (microchips)	All forms	Variations are stored using large numbers of transistors and capacitors within the chip. Only two possible variations are utilized.	Some designs have fixed information stored (ROM) whereas other have the flexibility to change the information (RAM).	Digital
Hard discs	All forms	Variations are stored as series of magnetic variations in the disc. Only two possible variations are utilized.	Hard discs operate in the same way as floppy disc. Large amounts of microchip memory can be equivalent to a hard disc.	Digital
DVDs	Video	Variations of light and sound are stored as a series of optical "bumps" or "pits" on the DVD track.	Minor damage to the disc can be accommodated while the data is being accessed. Major damage can prevent any data from being accessible.	Digital

Numbers in different bases

BINARY

The conversion between analogue and digital involves the conversion from normal numbers (decimal, or base 10) to binary (base 2). Normal numbers are represented by counting in powers of 10 so each digit represents 1, 10, 100, 1000 etc. Binary numbers are represented by counting in powers of 2 so each bit represents 1, 2, 4, 8, 16 etc.

Numbers are read from left to right. The left hand digit represents the largest power and the right hand digit represents the smallest power. In binary notation, the largest power is called the **M**ost **S**ignificant **B**it (**MSB**) and the smallest power is called the **L**east **S**ignificant **B**it (**LSB**).

e.g. $19 = 16 + 2 + 1 = 2^4 + 2^1 + 2^0$

19 in decimal = 10011 in binary

Most Significant Bit ↗ (first digit) — Least Significant Bit ↖ (last digit)

Base 10	2^4	2^3	2^2	2^1	2^0	Base 2
0	0	0	0	0	0	00000
1	0	0	0	0	1	00001
2	0	0	0	1	0	00010
3	0	0	0	1	1	00011
4	0	0	1	0	0	00100
5	0	0	1	0	1	00101
6	0	0	1	1	0	00110
7	0	0	1	1	1	00111
8	0	1	0	0	0	01000
9	0	1	0	0	1	01001
10	0	1	0	1	0	01010
11	0	1	0	1	1	01011
12	0	1	1	0	0	01100
13	0	1	1	0	1	01101
14	0	1	1	1	0	01110
15	0	1	1	1	1	01111
16	1	0	0	0	0	10000
17	1	0	0	0	1	10001
18	1	0	0	1	0	10010
19	1	0	0	1	1	10011
20	1	0	1	0	0	10100
etc						

ASCII

A given number of bits can represent a fixed number of different values. Each additional bit doubles the number of different possible values that can be represented.

Number of bits used	Number of different possible values
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	256
9	512
10	1024

Text written in English can contain a mixture of letters, numbers, symbols and punctuation marks. Additional characters are also needed to represent the formatting that takes place (new line, new paragraph etc). Computers often use a code known as ASCII (American Standard Code for Information Interchange). It is an 8-bit code representing 256 different possible characters and formatting codes.

Advantages and disadvantages of digital techniques (1)

CONVERSION BETWEEN ANALOGUE AND DIGITAL FORMS

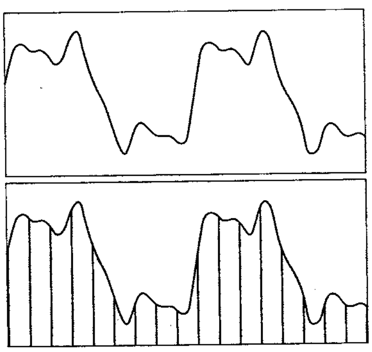
The conversion of everyday analogue information (e.g. music) into digital form (e.g. mp3 format on a computer) involves:

- Sampling the input information at regular intervals.
- Converting each sampled signal into one value from a fixed range of possible values (**quantum levels**).
- Converting each sampled quantum level into digital form (a binary number).

The accuracy of digital information can be improved by:

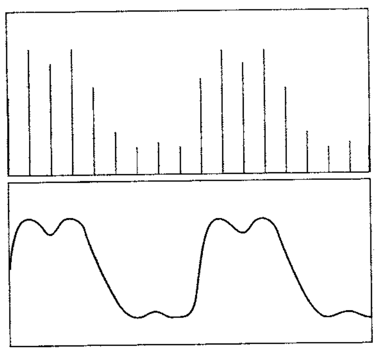
- Increasing the sampling frequency.
- Increasing the number of available quantum levels.

The output process involves converting the series of bits back into an analogue signal. Limitations in human sensing ability (ears and eyes) mean that some improvements of accuracy would not be distinguishable.



(a) Original signal

(b) Samples taken from signal



(c) Samples alone

(d) Signal 'reconstructed' from samples

Problem with sampling

Sampling too slowly misses high frequency detail in the original signal

Advantages and disadvantages of digital techniques

COMPARISON BETWEEN DIGITAL AND ANALOGUE TECHNIQUES

All processes introduce some amount of unwanted variations. For example unwanted additional variations (**noise**) can be added and the original signal can also be altered.

In analogue processes this affects the quality of the final signal. In digital processes only two possible signals are ever used so minor variations can be irrelevant to the final signal.

Electronic techniques can correct for missing or corrupted signals.

The process used for the storage and retrieval of information can also affect quality. Some retrieval processes (e.g. mechanical ones such as vinyl and tapes) damage the data that is being stored, making each subsequent retrieval lower in quality. In comparison other process (e.g. the optical techniques in a DVD) can be used to ensure that the original is not altered when data is accessed.

	Digital	Analogue
Complexity of code	There must be a complex set of rules for the conversion of input into digital signal and from digital to output.	Can be simple e.g. direct parallel between pressure variation of a sound and electrical p.d.
Quality	If the sample frequency and number of quantum levels are sufficiently high, then the output can be indistinguishable from the input.	Quality can be virtually indistinguishable from input but very liable to damage or corruption.
Reproducibility	Optical techniques can ensure that each subsequent retrieval is virtually identical.	Process of retrieval often affects quality of future retrievals.
Retrieval speed	Text and simple data can be retrieved at great speed. More complex data (video etc.) takes longer but selecting different sections of information often does not add significant time.	Often the retrieval process requires a significant time. Movement between different sections of the data can take significant time.
Portability of stored data	Modern miniaturization techniques have ensured that a large quantities of data can be stored in a very small device.	Although stored data can be compact, many analogue storage systems occupy significantly larger volume compared with digital alternative.
Manipulation of data	Manipulation of data can be easily achieved without significant corruption.	All manipulation will increase the possibility of data corruption.

IMPLICATIONS FOR SOCIETY OF EVER-INCREASING DATA STORAGE

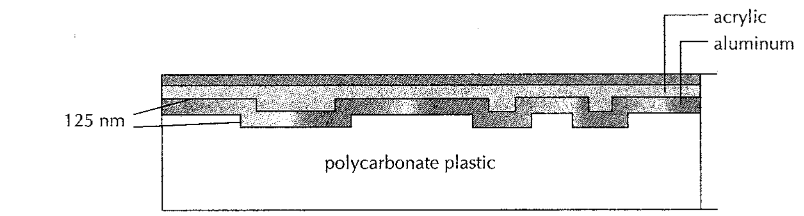
The increasing ease with which data can be electronically stored means that more information is being saved and this information is being accessed and shared by more people. This has several implications:

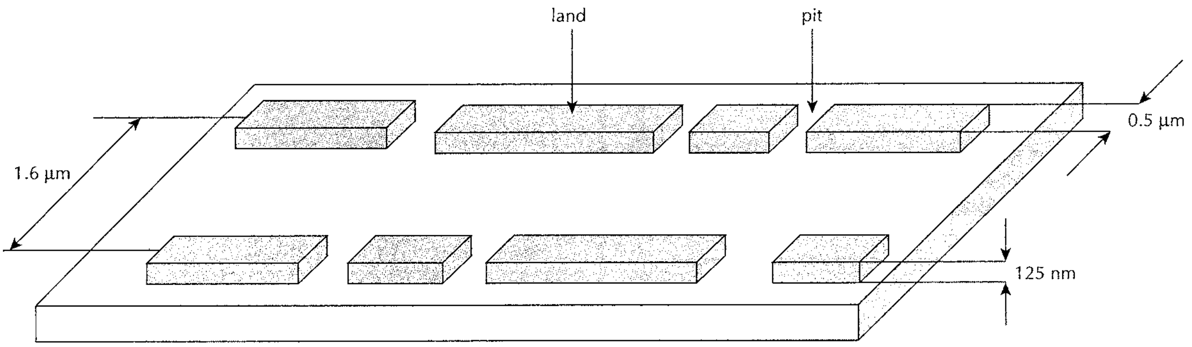
Moral / Ethical	• Digital technologies mean that information that is potentially problematic for society can be easily recorded and shared. • Issues concerning the access and ownership of electronic data. • Should there be any limits on what information an adult chooses to access or share with other adults? • Does a society have the right to control individuals' access to digital information? • If you are the subject of a stored piece of information, do you have any rights of access and/or control over its use? • To what extent does the state have the right to acquire identity data from the citizen? • The role of the historian is important, as is the need to create an archive policy. If only particular information is stored, then the information record will be biased.
Social	• Digital technology can be used to record and highlight abuses of human rights. • As more data is created, the access and storage of this information can control societies' opinions and views. • Individuals who do not have access to the Internet will be disadvantaged. • Since records are not on paper, what needs to be done to ensure the record is still available to subsequent generations?
Economic	• The cost of electronic data storage and transfer is very different from the cost of storage and transfer of more traditional techniques. • There will be an impact on the process of economic decision making which is often based on imperfect information. The distribution of data implies more perfect information and thus more competitive markets. • The above implies very quick price comparisons being possible and thus more stable markets, better control and a tendency for inflation to reduce. • It should result in better predictions for the future.
Environmental	• Electronic data storage could replace traditional techniques, thus resulting in a saving in resources. • In reality much paper is still wasted as information is printed off several times, creating a waste issue. • The resources needed for the manufacture of electronic data storage will be more sought after.

CDs and DVDs

HOW DATA IS STORED ON A CD

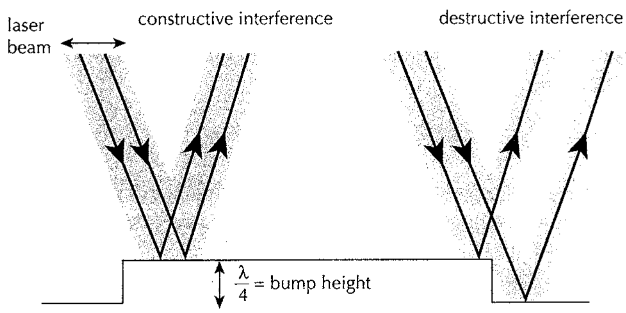
The track on a CD starts in the centre and works outwards in a spiral. It is made up of small 'bumps' or 'lands' and 'pits':





The information is read by sensing the amplitude of the reflection of a laser beam reflecting off the bumps and pits:

- The speed of rotation of the disc is controlled so that a constant length of track is scanned in a given time.
- The CD has a higher speed of revolution when the laser is reading near the centre compared with the outer edge.
- The laser beam is focused onto the track.
- When the beam reflects from a land or a pit, a strong signal is received.
- When the beam reflects from the edge between a land and a pit, destructive interference takes place and a weak signal is received.
- A strong signal represents 0 and a weak signal represents 1.



EXAMPLES

1. Laser light of frequency 6×10^{14} Hz is used in a laser. Calculate an appropriate depth of a pit on a CD.

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{6 \times 10^{14}} = 0.5 \times 10^{-6} = 500 \times 10^{-9} \text{ m} = 500 \text{ nm}$$

$$\text{depth of pit} \approx \frac{\lambda}{4} = \frac{500}{4} = 125 \text{ nm} \approx 1 \times 10^{-7} \text{ m}$$

2. A CD track moved from a radius of 25 mm to 58 mm with an average radius of 40 mm. The distance between sprials on the track is 1.6 µm. (a) Estimate the length of the track. (b) The scanning velocity is 1.2 ms^{-1}, estimate how long the CD will last. (c) It can store 700 Mbytes of information. What is the average length of track per bit of information?

a) Number of turns = 33 mm/1.6 µm = 20 625

Track length = $20\,625 \times 2 \times \pi \times 0.04 = 5184$ m ≈ 5.2 km

b) CD playing time = 5184 m/1.2 = 4320 s = 72 minutes

c) Average length per bit = 5184 m/7 × 10^8 × 8 = 0.9 µm

3. Estimate the playing time of a 700 Mbyte CD storing stereo music using 16 bit sampling.

Max audio frequency = 20 kHz
∴ sampling frequency ≈ 40 kHz

Number of bits every second for each channel = 40 000 × 16 = 6.4×10^5 bits

Total number of bits per second for stereo = 1.28×10^6 bits

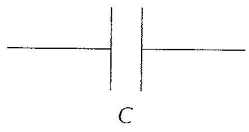
Total storage capacity of CD = 7×10^8 bytes = 56×10^8 bits

Maximum time for CD = 56 = $10^8/1.28 \times 10^6$ = 4375 s ≈ 73 minutes

Capacitance and charge-coupled devices (CCDs)

CAPACITANCE

Capacitors are devices that can store charge. The charge stored q is proportional to the p.d. across the capacitor V and the constant of proportionality is called the capacitance C.

Symbol: 

$$C = \frac{q}{V}$$

charge in coulombs (q); capacitance in farads (C); p.d. in volts (V)

The farad (F) is a very large unit and practical capacitances are measured in µF, nF or pF.

1 F = 1 C V^{-1}

A measurement of the p.d. across a capacitance allows the charge stored to be calculated.

IMAGE PARAMETERS

Quantum efficiency

The pixels in a perfect CCD would each emit one photoelectron for each photon incident on its surface. Practical CCDs do not achieve this level of efficiency. Quantum efficiency QE is the ratio of the number of photoelectrons emitted to the number of photons incident on the pixel.

$$QE = \frac{N_e}{N_p}$$

Quantum efficiencies depend on the design on the CCD and the wavelengths involved and typically vary between 20% and 90%.

Magnification and resolution

Lenses are used to focus an image of the object onto the CCD. Magnification is the ratio of the length of the image on the CCD to the length of the object.

Two points on an object may be just resolved on a CCD if the images of the points are two pixels apart.

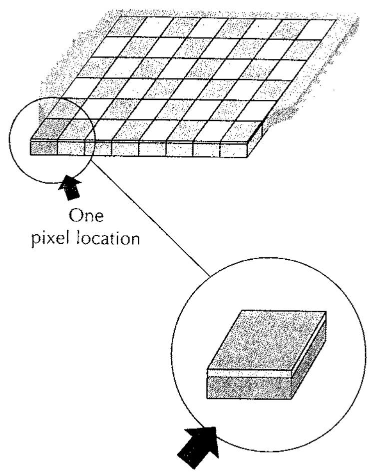
EXAMPLE

A digital camera is used to photograph an object. Two points on the object are separated by 0.0020 cm. The CCD in the camera has a collecting area of 16 cm^2 and contains 4.0 megapixels. The magnification of the camera is 1.5. Can the images of the points be resolved?

Area corresponding to each pixel $16 \times 10^{-4}/4 \times 10^{6} = 4.0 \times 10^{-10}$ m^2
Separation of pixels = $\sqrt{(4.0 \times 10^{-10})} = 2.0 \times 10^{-5}$ m
Equivalent separation on the object = $2.0 \times 10^{-5}/1.5 =$ 0.0013 cm
Distance between two pixels $<$ 0.0020 cm so image can be resolved

CHARGE-COUPLED DEVICE (CCD)

A CCD is a silicon (semiconductor) microchip that can be used to electronically record an image focused onto its surface. The surface is divided into a large number of small areas called **pixels**.



There are four stages to recording a digital image using a CCD:

- During a photo exposure, each element within the CCD generates a charge proportional the incident light as a result of the photoelectric effect.
  - Each pixel converts light energy into electrical energy using the photoelectric effect.
  - As more photons are incident on a pixel, more electrons are emitted.
- The charge is collected in different pixels.
  - The pixel behaves as a capacitor and a charge builds up on each pixel.
  - The amount of charge is proportional to the number of photons (which is also related to the intensity of the light) incident on the pixel.
  - The p.d. across each pixel is proportional to the number of photons incident on the pixel.
- The charge collected from each pixel is transferred in turn by 'coupling' charges from one pixel to the next in turn.
  - Storage changes can be transferred along a line of pixels in sequence.
  - The signal processing takes place line by line to ensure the charge on each pixel is recorded.
- Individual charge packets are converted to an output voltage and then digitally encoded.
  - The value of the p.d is measured and converted into a digital signal in binary code.
  - The light intensity information from each pixel can be stored along with another digital signal representing the position of the pixel on the surface.
  - The signals from each pixel can be stored.
  - The information can be used to reconstruct the image as the information from each pixel has recorded the different light intensities in different parts of the image.

HL Uses of CDs

PRACTICAL USES OF CCDS

CCDs are used for image capturing in a large range of the electromagnetic spectrum. The following list provides some examples.

Device	Comment
Digital cameras	Very convenient to take and share photographs, but image quality can be lower than traditional film unless camera is of high quality (which is more expensive). In order to create a colour photograph, the image is analysed three times – once each for red, green and blue.
Video cameras	Digitized images are usually better quality than analogue images stored on magnetic videotape and are easier to store and transport. It is possible to continuously record video without interruption during playback. Searches are faster and easier to perform. Digital storage is fast and utilizes re-usable media – useful for security recordings.
Telescopes	Sensitivity of CCDs is better than traditional film and allows for detailed analysis over a range of frequencies. Exposure times are reduced. CCDs also allow for remote operation of telescopes. The Hubble space telescope is in orbit.
Medical X-ray imaging	Traditional X-rays involve the use of film. Digital X-rays can have better contrast and have the advantage of being able to be processed, allowing the images to be easily compared using imaging techniques. Information can be quickly and easily shared between distant hospitals and storage and access can be improved.
Scanners	Everyday images can be scanned into digital form using a scanner. Fax machines scan text and transmit the image along telephone lines.

	Quality of the processed image
Quantum efficiency	The greater the QE, the greater the sensitivity of the device.
Magnification	A greater magnification means that more pixels are used for a given section of the image. The image will be more detailed.
Resolution	The greater the resolution, the greater the amount of detail recorded. An improvement in resolution will mean a given image will occupy more memory.

Advantages of CCDs compared with use of film:

- Each photo does not require the use of film and is thus cheaper.
- Traditional films have a QE of less than 10% whereas values of over 90% are achievable for some frequencies for CCDs. This means that very faint objects can be photographed.
- The image is digital so it can be enhanced and edited using electronic processing techniques.
- Image can be viewed virtually immediately – there is no processing time.
- Storage and archiving of a large number of photographs is easy.

IB QUESTIONS – DIGITAL TECHNOLOGY

1 Estimate the minimum number of bits that are needed

(a) to represent each character in a simple sentence written in English

(b) to write this question. [4]

2 Two friends talk on the telephone for 15 minutes. The sound is transmitted by using 8 bit sampling at a sampling frequency of 8 kHz. Calculate the total number of bits of information that have been transmitted. [4]

3 Outline how the interference of light is used to recover information stored on a CD. [6]

4 The wavelength of light used in a CD player is 500 nm. Calculate the bump heights on the CD. [2]

5 State and explain five advantages of storing information in digital rather than analogue form. [5]

6 **(a)** A 3μF capacitor is charged to 240 V. Calculate the charge stored. [1]

(b) Estimate the amount of time it would take for the charge you have calculated in **(a)** to flow through a 60 W light bulb connected to the 240 V mains electricity. [2]

(c) The charged capacitor in **(a)** is discharged through a 60 W 240 V light bulb.

(i) Explain why the current during its discharge will not be constant. [2]

(ii) Will the bulb light during discharge? Explain your answer. [2]

7 A satellite system takes an image of the surface of the Earth. Each image covers 100 km^2 and is recorded by a CCD of area 25 cm^2.

(a) Calculate the magnification of system. [2]

(b) The resolution of the system is 10 m.

(i) Calculate the separation of the pixels on the CCD. [2]

(ii) Find the number of pixels on the CCD. [2]

8 Outline how

(i) the image on a CCD is digitized

(ii) the image stored in a CCD is retrieved. [6]